

# Lateral photocurrent spreading in single quantum well infrared photodetectors

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Lateral physical effects in single quantum well infrared photodetectors (SQWIPs) under non-uniform illumination over detector area are considered. These effects are due mainly to the in-plane transport of the photoinduced charge in the QW. The length of the lateral photocurrent spreading is determined by the in-plane conductivity of the carriers in the QW and characteristic time of the QW recharging, and can be as large as  $10^1$ – $10^4$   $\mu\text{m}$ . Closed-form analytical expressions for SQWIP responsivity for modulated infrared signal and modulation transfer function are obtained. Possible techniques to suppress lateral photocurrent spreading are discussed.

73.61.Ey, 73.50.Pz, 73.40.Kp

Quantum well infrared photodetectors (QWIPs) attracted a great deal of attention in the last decade.<sup>1</sup> Recently a number of new steady-state and transient physical effects in QWIPs have been predicted theoretically and confirmed experimentally.<sup>2–5</sup> Practically all theoretical studies of QWIPs assumed that infrared radiation (IR) intensity is constant over the QWIP area, and that the physical processes are uniform in the plane of the QWs. In practical conditions, however, IR radiation intensity inside QWIP can be laterally non-uniform due to the non-uniformity of the incoming infrared signal, light diffraction, reflection, scattering and interference in QWIP, and other reasons. The non-uniformity of the photoexcitation from the QWs and related lateral effects can change the mechanism of operation and characteristics of QWIPs. The lateral effects are especially critical for large-area pixelless QWIP-LED infrared imaging devices.<sup>6,7</sup> The lateral spreading of the photocurrent in QWIP determine the spatial resolution of the transformed infrared image, and hence the imaging functionality of the device. One of the possible reasons for image smearing in QWIPs with large photocurrent gain is the lateral spreading of the photoinduced charge in the QWs near the emitter and resulting broadened current injection from the emitter.<sup>8</sup>

In this letter we study theoretically the lateral photocurrent spreading and related physical effects in QWIP with single QW (SQWIP). This case allows analytical treatment due to its simplicity and thus leads to a better understanding of the photocurrent spreading effects in QWIPs. Also, studying SQWIPs will provide a worst-case estimate of the lateral spreading in QWIPs with multiple QWs. In this letter we show that the lateral photocurrent spreading in SQWIP is determined by the

photoinduced charge screening and transport in the QW, and, in particular, by the in-plane conductivity of the 2D electron gas (2DEG) in the QW. The scale of the lateral spreading can be extremely large ( $10^1$ – $10^4$   $\mu\text{m}$ ).

The SQWIP structure under consideration is similar to that considered earlier<sup>9–11</sup> and is typical for practical SQWIPs.<sup>12,13</sup> In short, SQWIP contains a narrow single-level QW separated by wide undoped barriers from the contacts. For concreteness, we consider  $n$ -type SQWIP. Electron concentration in the QW is high ( $10^{11}$ – $10^{12}$   $\text{cm}^{-2}$ ). Under applied voltage, electrons injected from the emitter can be collected by the collector or captured into the QW. The dynamics of the QW recharging is determined by the balance between the capture of injected electrons and electron escape from the QW.

Let us first consider qualitatively the physical processes in SQWIP under non-uniform illumination conditions (see Fig. 1). We are interested in the lateral distribution of the photocurrent at the SQWIP output (collector contact). Narrow infrared beam incident on SQWIP excites locally electrons from the QW to the states above the barriers. These electrons reach collector or emitter contact at the same lateral position (due to negligible out-diffusion) and contribute to the photocurrent (primary photocurrent). Originally localized photoinduced charge in the QW induce a lateral electric field, which causes transport of the 2DEG in the QW towards the excitation area. Due to the high 2DEG conductivity, the resulting area of QW space charge becomes wide, inducing injection from the emitter over a wide area. In the case of the large photocurrent gain, most part of the injection current reach the collector, resulting in significant spreading of the output photocurrent. Thus, the main physical mechanisms of the lateral photocurrent spreading in SQWIP are the lateral transport of the 2DEG in the QW and resulting spreading of the photoinduced charge in the QW and injection from the emitter.

To quantitatively describe the SQWIP operation under non-uniform illumination conditions, we use a 2D model of SQWIP which generalizes the 1D model<sup>9–11</sup> for the case of lateral (along the  $y$ -axis) non-uniformities of physical quantities. We use the small-signal approximation, assuming that the photoemission from the QW due to the non-uniform illumination is much weaker than the total emission due to thermo- or photo-excitation. The sheet electron density in the QW  $\delta\Sigma$  is governed by the continuity equation (in the drift-diffusion approximation):

$$e \frac{\partial \delta\Sigma}{\partial t} + \frac{d}{dy} \left[ e\mu\Sigma \frac{d\delta\varphi}{dy} - eD \frac{d\delta\Sigma}{dy} \right] = (1 - \beta) \delta j_e(E_e) - e\sigma\Sigma \delta I, \quad (1)$$

where  $\delta\varphi$  is the QW potential,  $j_e$  is the injection current density from the emitter dependent on emitter electric field  $E_e$ ,  $\beta$  is the probability of the electron transport from emitter to collector,  $\sigma$  is the photoionization cross-section,  $\mu$  and  $D$  are the mobility and diffusion coefficient of the 2DEG, and  $\delta I$  is the infrared radiation intensity. All small-signal quantities denoted by the  $\delta$ -symbol depend on time and the  $y$ -coordinate. In this work we are interested in the case of the long-range lateral non-uniformities with the scale much larger than the thickness of the SQWIP active region ( $\lambda \gg W \sim 0.1 \mu\text{m}$ ), which corresponds to practical experimental conditions. In this case the Poisson equation reduces to the one-dimensional equation (along the  $x$ -axis), which can be solved analytically to obtain the QW potential:

$$\delta\varphi(y, t) = -\frac{e\tilde{W}}{\varepsilon\varepsilon_0} \delta\Sigma(y, t). \quad (2)$$

Here  $\tilde{W} = W_e W_c / W$  is the reduced SQWIP thickness ( $W_e$  and  $W_c$  are the effective emitter and collector barrier thicknesses,<sup>11</sup> respectively, and  $W = W_e + W_c$ ), and  $\varepsilon\varepsilon_0$  is the dielectric permittivity. We assumed that the contacts are highly conductive, i. e. respond instantaneously to the change of the QW charge. The injection current density is given by  $\delta j_e = \gamma_e \delta E_e = \gamma_e \delta\varphi / W_e$ , where  $\gamma_e = dj_e / dE_e$  is the differential conductivity of the injection barrier. The total photocurrent density in SQWIP is given by the formula:

$$\delta j(y, t) = e\sigma\Sigma\delta I \left[ \zeta \frac{W_c}{W} - (1 - \zeta) \frac{W_e}{W} \right] + \delta j_e \left[ \beta + (1 - \beta) \frac{W_e}{W} \right], \quad (3)$$

where  $\zeta$  is the probability for the photoexcited electron to reach the collector ( $(1 - \zeta)$  is the probability to reach the emitter). The first term in eq. (3) corresponds to the current induced by the electrons excited from the QW (primary photocurrent), and the second term corresponds to the current due to the electrons injected from the emitter (secondary or multiplied photocurrent).

The solution of eqs. (1–3) for the case of infrared radiation modulated harmonically in space and time  $\delta I(y, t) = \delta I \exp[i(ky - \omega t)]$  is given by  $\delta j(y, t) = \delta j(k, \omega) \exp[i(ky - \omega t)] = g(k, \omega) e\sigma\Sigma\delta I(y, t)$ , where the photocurrent gain  $g$  is expressed as:

$$g(k, \omega) = \left[ \zeta - \frac{W_e}{W} \right] + \left[ \frac{\beta}{1 - \beta} + \frac{W_e}{W} \right] \times \frac{1}{1 - i\omega\tau + \lambda^2 k^2}. \quad (4)$$

The characteristic time constant  $\tau$  and length  $\lambda$  are given by the formulas:

$$\tau = (\varepsilon\varepsilon_0 W) / [(1 - \beta)\gamma_e W_c], \quad (5)$$

$$\lambda = \sqrt{[e\mu\Sigma\tilde{W} / (\varepsilon\varepsilon_0) + D]\tau} \approx \sqrt{v\tilde{W}\tau}, \quad (6)$$

where  $v = \sigma_{2D} / (\varepsilon\varepsilon_0)$  is the velocity of charge relaxation in 2DEG with conductivity  $\sigma_{2D} = e\mu\Sigma$ .<sup>14</sup> Formula (4) generalizes a previously obtained formula for the photocurrent gain in the 1D case ( $k = 0$ ).<sup>11</sup> The lower limit of the gain  $g = \zeta - W_e / W$  is determined by the primary photocurrent. The dispersion of the gain is due to the cut-off of the injection from the emitter, which is caused by the “freezing” of the QW recharging processes at high frequencies  $\omega \gg 1/\tau$ , or lateral smearing of the photoinduced charge at high spatial frequencies  $k \gg 1/\lambda$ . The characteristic time constant  $\tau$  is the QW recharging time, or the time of establishing equilibrium at the injecting contact. It depends strongly on operating conditions and SQWIP design, and its value can span over a wide range  $\sim 10^{-9} - 10^{-3}$  s.<sup>10</sup> It should be noted that the time constant  $\tau$  determines the frequency dispersion of various SQWIP characteristics – admittance, noise current, photocurrent, etc.<sup>10,11</sup> The characteristic length  $\lambda$  can be interpreted as an effective diffusion length  $\sqrt{\tilde{D}\tau}$ , where  $\tau$  can be considered as the life-time of the non-equilibrium electrons in the QW, and  $\tilde{D} = v\tilde{W}$  is an effective diffusion coefficient. However, this effective diffusion is different from the real diffusion caused by the gradient of carrier concentration. The lateral out-diffusion is related to the drift of the QW electrons in the in-plane field created by the non-uniform distribution of the QW charge and charges induced on the emitter and collector contacts. The effective diffusion coefficient can also be represented as  $\tilde{D} = 1/(RC)$ , where  $R$  is the sheet resistivity of the 2DEG, and  $C = \varepsilon\varepsilon_0 / \tilde{W}$  is the effective SQWIP capacitance (compare with ref. 15). An estimate of  $\tilde{D}$  for typical SQWIP structures ( $W_e = W_c = 500 \text{ \AA}$ ,  $\Sigma \sim 10^{11} - 10^{12} \text{ cm}^{-2}$ ,  $\mu \sim 10^3 \text{ cm}^2/\text{Vs}$ ) gives  $\tilde{D} \sim 10^2 - 10^3 \text{ cm}^2/\text{s}$ , which is much larger than the typical values of diffusion coefficient  $D \sim 10 \text{ cm}^2/\text{s}$ . An estimate of the characteristic length gives  $\lambda \sim 10^1 - 10^4 \mu\text{m}$  ( $\lambda \sim 100 \mu\text{m}$  for SQWIP presented in ref. 13), which can be comparable with or larger than the lateral dimensions of SQWIPs.

Let us now consider a spatial resolution of SQWIP when it is used in QWIP-LED imaging device. To characterize the spatial resolution of QWIP-LED, we calculate the modulation transfer function<sup>16</sup> (MTF) of SQWIP, which is the ratio of the amplitude of the small-signal photocurrent for modulated illumination to that for the uniform steady-state illumination:

$$\mathcal{M}(\omega, k) \equiv \frac{\delta j(\omega, k)}{\delta j(0, 0)} = \left[ \left( \zeta - \frac{W_e}{W} \right) + \left( \frac{\beta}{1 - \beta} + \frac{W_e}{W} \right) \times \frac{1}{1 - i\omega\tau + \lambda^2 k^2} \right] \left( \frac{\beta}{1 - \beta} + \zeta \right)^{-1}. \quad (7)$$

For SQWIPs with large photocurrent gain ( $\beta \rightarrow 1$ ) this formula reduces to  $\mathcal{M} = (1 - i\omega\tau + \lambda^2 k^2)^{-1}$ , so that MTF is strongly degraded if  $\omega \gg 1/\tau$  or  $k \gg 1/\lambda$ . On

the other hand, in SQWIPs with  $\beta = 0$  (this case is realized, for example, for SQWIP with tunneling injection from emitter to the QW<sup>12</sup>) MTF approaches a value of  $\mathcal{M} = 1 - W_e/(\zeta W)$  in the limit of high-frequency time or spatial modulation. Theoretically, one can expect very large (negative) values of MTF in the case  $\zeta \ll 1$ .

If the characteristic spreading length  $\lambda$  exceeds the lateral SQWIP dimension, the variation of the electron density in the QW is spread uniformly over the whole SQWIP area under non-uniform illumination conditions. In this case all physical processes are essentially one-dimensional. This effect can play both positive and negative role for QWIP operation. Under localized excitation, the whole QWIP area work as a photosensitive area. This effect results in lower photocurrent densities and helps to avoid undesirable effect of responsivity non-linearity at high excitation power.<sup>4</sup> On the other hand, if large-area SQWIP has only one defect resulting in the QW-collector leakage, the whole SQWIP will be shortened down and thus defective. For SQWIP operation under low-power illumination and electrical read-out of output signal, the photocurrent spreading effects are not important, since the total photocurrent is integrated over the SQWIP area.

Lateral spreading of the photoinduced charge in the QWs and resulting photocurrent spreading can limit the spatial resolution and even kill the imaging capabilities of pixelless QWIP-LED devices. The guidelines for decreasing spreading length  $\lambda$  and, therefore, for improving spatial QWIP-LED resolution, are obvious from eq. (6). One possible solution is to decrease  $\tau$  by designing SQWIP with very high differential conductivity of the injection barrier  $\gamma_e$ . Another way is to decrease the in-plane conductivity (mobility) of carriers in the QW. This can be achieved, for example, by periodic modification of the QW structure (e. g. by QW intermixing), or by using an array of weakly coupled quantum dots instead of QW.<sup>17</sup> The decrease of the carrier mobility can be also achieved by using *p*-type SQWIP (*p*-type doped QW), since the hole mobility is typically much lower than the electron mobility (in GaAs/AlGaAs system).

In conclusion, we considered physical effects responsible for lateral photocurrent spreading in SQWIPs. Analytical expressions for the characteristic spreading length, photocurrent gain, and MTF were obtained.

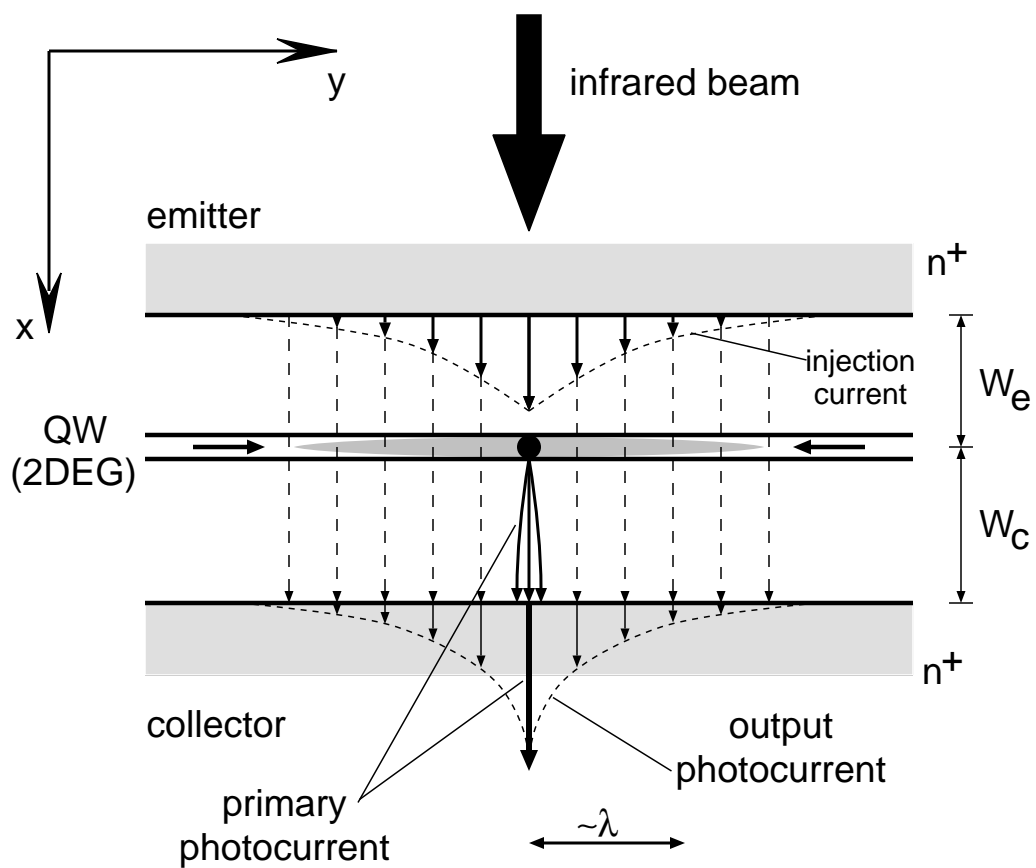
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FIG. 1. (a) Structure and physical effects in SQWIP under localized excitation and (b) conduction band diagram of SQWIP.

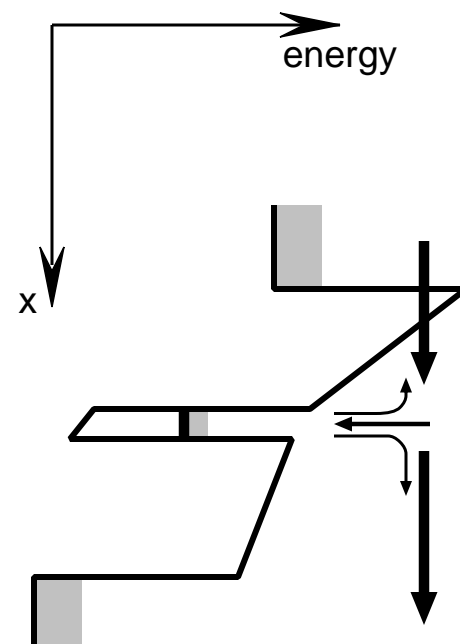
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(a)



(b)

Fig.1  
M.Ershov, APL